Project Report: Evolution of Atmospheric O_2, Climate, and Biosphere − Hiroshi Ohmoto

Lead Team:	***Pennsylvania State University***
Project Title:	***Evolution of Atmospheric O_2, Climate, and Biosphere − Hiroshi Ohmoto***
Project Investigator:	***Hiroshi Ohmoto***

Project Progress

We have continued to accumulate a variety of geochemical evidence in Precambrian rocks suggesting the atmosphere and oceans became oxygenated and the oceans and land were colonized by diverse organisms by 3.2 billion years ago. This date is at least 1 billion years earlier than most geoscientists have accepted. The investigated rock types include: (a) marine shales and greywackes; (b) paleosols; (c) red beds; (d) banded iron formations; (e) ores (volcanogenic massive sulfides, uraninite); and (f) igneous rocks (volcanics and plutonics). These rocks range from 3.4 to 1.8 billion years in age, and they were systematically collected from the Kaapvaal Craton in South Africa, the Pilbara−Hamersley district in Australia, the Abitibi greenstone belt in Canada, and the Lake Superior district in Canada/USA. The types of geochemical investigations have included: (a) organic geochemistry of organic matter (carbon isotopes, C/P/N/H ratios, C content); (b) Fe geochemistry (Fe/Al, Fe/Ti, Fe^{3+}/Fe^{2+}); (c) sulfur geochemistry (sulfur isotopes, S/C/Fe ratio, S content); (d) rare earth element geochemistry (Ce anomaly); and (e) trace element geochemistry (Mo, U, V, etc).

We have conducted laboratory experiments to determine the dissolution rates of some important redox−sensitive minerals (i.e., uraninite and pyrite) as a function of O_2 content and pH of solutions. These data have become essential in relating the geochemical data on natural rocks (see above) to the atmospheric O_2 level.

Based on the analyses of laboratory data on the kinetics of oxidation of organic matter and of the carbon contents of marine sediments, we have established a quantitative model for the geochemical cycle of oxygen. We have suggested that the atmospheric O_2 level has been maintained within ±50% of the present level since the emergence of oxygenic photosynthesis by two major negative feedback mechanisms. One is an increase in the burial flux of organic matter in marine sediments with decreasing pO_2, and the other is a decrease in the O_2 consumption flux during soil formation with decreasing pO_2.

Highlights

- The discovery of the large−scale formation of laterites, redbeds, and terrestrial microbial mats in the Kaapvaal Craton, South Africa, around 2.3 billion years ago¾This discovery, reported in *Geology* (June, 2002), is strong evidence for the development of an oxygen−rich atmosphere and terrestrial biosphere prior to 2.2 billion years ago.

- The discovery of 2.6 billion−year−old redbeds of groundwater−origin in Ontario, Canada¾Preliminary results from our geochemical investigations support the theory that these redbeds were formed by oxygenated groundwater about 2.6 billion years ago; this implies that the development of an oxygenated atmosphere occurred prior to 2.3 billion year ago.

- The discovery of remnants of microbial mats developed in submarine hydrothermal brine pools 2.7 billion years ago¾In marine shales deposited together with massive sulfide deposits in the Abitibi district of Ontario, Canada, we have discovered remnants of microbial mats that were composed of heterotrophic microbes, probably including methanogens and sulfate reducing bacteria.

- The discovery of evidence of the development of complex ecosystems on land 2.6 billion years ago¾We reported in *Nature* (2000) the discovery of remnants of microbial mats developed on soils 2.6 billion years ago in the Transvaal district, South Africa. Further investigations of this organic matter suggest the microbial mats were composed of photoautotrophs (probably cyanobacteria) and chemolithic heterotrophs.

- The discovery in 3.2−billion−year−old sediments of the early development of the microbially mediated redox cycling of nitrogen¾Nitrogen isotopic compositions of Archean shales suggest the very early evolution of a variety of nitrogen−utilizing organisms, including those involved in N_2−fixation , nitrification, denitrification, and ammonification.

- The discovery in Archean shales of the early development of modern−style geochemical cycles of C, S, Fe, P, Mo, and U¾This finding also supports the theory postulating the early development of an oxygenated atmosphere−ocean system and of a fully developed marine and terrestrial biosphere.

- The understanding of the mechanisms controlling the atmospheric oxygen level through geologic time¾Based on theoretical, experimental, and field data, we (Lasaga and Ohmoto, 2002, *Geochimica et Cosmochimica Acta*) have developed a quantitative model illustrating that the atmospheric oxygen level has been maintained within ±50% of the present level since the first appearance of cyanobacteria by two major negative feedback mechanisms: one is the production of O_2 by the burial of organic matter in marine sediments and the other is the consumption of O_2 by weathering of soil kerogen.

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 2:*** Origin of Life?s Cellular Components
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 10:*** Natural Migration of Life
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change
- ***Objective No. 15:*** Earth?s Future Habitability

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mission to Early Earth	Sherry Stafford (graduate student at Univ. of Pittsburgh) participated in the field trip in Pilbara, Australia organized by the Focus Group last summer Several of us participated in the discussion sessions. Ohmoto has been coordinating a Japanese drilling project in the Pilbara district, Australia. This project will be linked to the drilling project by the Mission to Early Earth Focus Group.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Field Expeditions

Field Trip Name: Banded iron formations, red beds, and paleosols.	
Start Date: 07/03/2001	***End Date:*** 07/22/2001
Continent: North America	***Country:*** Canada and USA
State/Province: Ontario, Canada; Minnesota, USA	***Nearest City/Town:*** Kirkland Lake, Timmins, Wawa, and Thunder Bay, Canada; Hibbing, MN
Latitude: 48 N	***Longitude:*** 81 W
Name of site(cave, mine, e.g.): Sherman mine, Adams mine, Kidd Creek mine, Steep Rock mine, Minntac mine; Shebandwan road cut	***Keywords:*** Archean and early Proterozoic banded iron formations; Archean red beds; Archean paleosols
Description of Work: To investigate the eologic relationships between the Algoma−type banded iron formations (BIF) and volcanogenic massive sulfide deposits. To investigate the geologic differences between the Algoma−type BIFs and the Lake Superior−type BIFs. To investigate the geologic setting of the 2.6 Ga Shebadwan red bds. To collect samples of BIFs, red beds, and paleosols for geochemical investigations.	
Members Involved: Hiroshi Ohmoto, Yumiko Watanabe, Ekaterina Bazilevskaya, and Hiroaki Ikemi.	

Cross Team Collaborations

Clarke Johnson, Univ. of Wisconsin (Jet Propulsion Laboratory (JPL) − Wisconsin Team): collaboration on the Fe isotope geochemistry of banded iron formations and paleosols. One of Ohmoto's recent Ph.D. students (Dr. Kosei Yamaguchi) has recently joined the Johnson research group to carry out this collaborative research.

Douglas Rumble, Geophysical Laboratory (Carnegie Team): collaboration on sulfur isotope geochemistry (mass independent isotope fractionation) on Archean sedimentary rocks. Dr. Shuhei Ono, one of Ohmoto's Ph.D. students, was given opportunities to perform sulfur isotope analyses in Dr. Rumble's laboratory. Ono has also built an analytical system at Penn State that is modeled after the system in Rumble's Laboratory.

Paul Hoffman and Galen Halverson of the Harvard Team: We have provided Galen Halverson the analytical facility for his research on sulfur isotope geochemistry of Neoproterozoic carbonates.